Positive and negative sequence currents optimization to improve voltages during unbalanced faults

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***Abstract*—Grid faults constitute a series of unfortunate events that compromise power systems. With the increasing integration of renewables and their associated power electronics converters, the injected currents are controllable, but at the same time, they have to be limited so as not to damage the semiconductors. This poses the challenge to determine the combination of currents that improves the most the voltages at the point of common coupling. In this paper, such an issue is approached from an optimization perspective. Solving the optimization problem allows comparing its solutions with respect to the ones obtained by following the grid code control laws. Two fundamental scenarios are presented: one with a single converter, and another with two converters. Several parameters are varied for all kinds of faults to spot the changes on the currents, such as the severity of the fault, the distance of a hypothetical submarine cable, and the resistive/inductive ratio of the impedances. Overall the results indicate that injecting only reactive power is not always the preferable choice. While grid codes are not optimal, they can be regarded as near-optimal decision rules.**

***Index Terms*—VSC, Grid-Support, Reference Optimization, Asymmetrical Fault, Current Saturation**

I. Introduction

The rise in renewable energies has carried along with it the inclusion of Voltage Source Converters (VSC) as a means of coupling energetic resources to the grid while providing controllability [1]–[3]. Adopting such power electronics equipment has induced a progressive shrinkage on synchronous generators' influence in power systems. The high flexibility of VSC control enables advanced grid-support control, which could enhance the system performance during the fault and ensure a fast recovery after the fault clearance. However, compared to electrical machines, VSCs cannot withstand overloads [4]. Indeed, current (and also voltage) limitations cause VSC to behave differently. They reach what is called a saturated state. Many equilibrium points may arise as a result of that, especially in grids formed by multiple converters operating in critical conditions. The solution to such systems is also likely to become an arduous task to compute, as saturation states are defined by non-linear equations, or in more detail, by piecewise functions.

Not only do currents have to be constrained to not exceed the limitations, but they also have to collaborate on improving the voltages [5]. This becomes visible when looking at the requirements imposed by Transmission System Operators (TSO) in its grid codes [6], [7]. Although this was not the case years ago, when wind power represented a small percentage of the electricity mix, nowadays wind power plants have to control active and reactive power [8]. Besides, they have to transiently support the faults. The latter aspect is often referred to as low voltage ride through (LVRT) [9], [10]. The traditional approach to raise the voltage at the point of common coupling is to inject reactive power proportionally to the severity of the fault [8], [11]. During the analysis of faults, it is often the case that voltages are decomposed into positive, negative, and zero sequence values. By doing so, the study of the fault is expected to be simplified, and in addition to that, some intuition can be build from inspecting the positive and negative sequence voltages. A concerning unbalanced fault is such that substantially decreases the positive sequence voltage with respect to the nominal voltage while the negative sequence voltage increases. Both sequences have to be thoroughly controlled, as discussed in [11], [12].

Nevertheless, for the most part, grid codes only specify reactive power injection during faults [13], [14]. This is because transmission networks are often considered to have an inductive characteristic. The influence of the grid impedance characteristics of the system optimized under an equilibrium state is covered in [12], where the authors express the currents to inject as a function of the voltage and the impedances. A recursive relation between the voltage and the current is found, which invalidates the possibility of working with a closed-form expression from where to compute the optimal currents solution. Expressions of the same nature are proposed in [15], where instead of attempting to solve the optimization problem, a control parameter is introduced. This takes various values, but no analysis is carried out to determine the optimal choice. The effect of varying this control parameter is studied in [16], although it is not computed with a systematic approach, but rather, manually. Reference [17] proposes a maximum allowed support (MAS) control scheme that is said to provide the maximum voltage support and simultaneously satisfying the current limitations. The study does not explicitly indicate how the current is distributed among the real and the imaginary positive and negative sequence components, and variations in input parameters are rather limited. Another voltage support scheme is presented in [18], where the injected currents depend neither on the active power nor the filter resistance. In addition, positive and negative sequence grid voltage values are imposed, which facilitates the obtention of the steady-state current values. A variation of the grid code requirements is depicted in [19]. The authors found it to provide better results than conventional grid codes. The majority of the grid support strategies described above are compared and summarized in [20]. It is worth mentioning that the systems under study considered in these references include a single VSC. Further conclusions are expected to be extracted from examining a two-converter case study.

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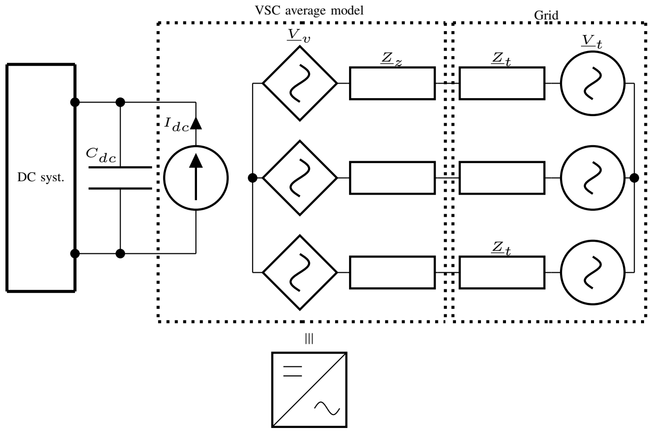

Fig. 1: Average model of a VSC connected to the grid

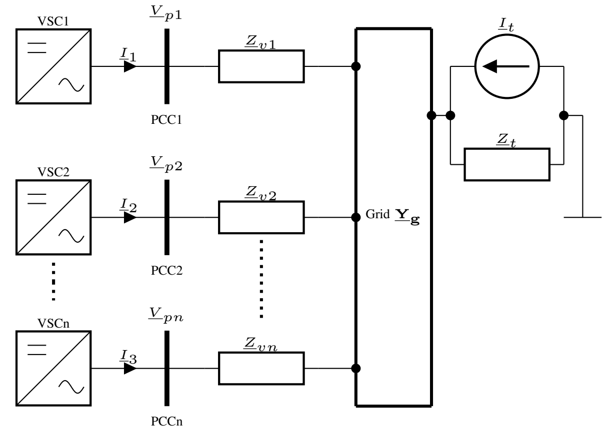

Fig. 2: Single-phase representation of a complete system

This paper proposes a methodology to identify the optimized system equilibrium point during the fault considering converters' current limitations. Two other control rules are implemented. One focuses on solving the optimization problem but in addition to the other constraints, it is restricted to only injecting reactive power. The third control rule follows the implementation of grid code specifications with its characteristic droop profile. These three options are tested for both balanced and unbalanced faults, where this last category includes the line to ground, the line to line, and the double line to ground faults. First, a basic system with a single converter is studied. Then, the analysis is repeated for a system with two converters in order to identify their interaction in saturated states.

Two main contributions come from this paper. On the one hand, it indicates the preferable injected currents under diverse conditions. A deeper understanding of the optimality of the solutions is expected to be gained from it. On the other hand, comparisons between the optimal solution and the one obtained by following the grid code are presented. An assessment about the convenience of grid codes to support faults can be derived, which should be useful when proposing future modifications in order to evolve towards more resilient grids.

II. Formulation

A. System modeling

VSCs are elements that interconnect DC systems with AC systems. As shown in Figure 1, they can be modeled following the so-called average model, where the switchings of the semiconductors are excluded. The VSC has been assumed to be connected to the AC grid with a filter in between denoted by $\underline{Z}_z$. The control strategy of the VSC consists of adjusting the voltages appropriately so that currents can indirectly meet the references [21].

Power systems are likely to involve more than a single converter. Therefore, the modeling is approached from a generalized perspective. Figure 2 presents the modeling for a system with n converters. They are connected to a grid which has been split into a passive part, only formed by impedances and denoted by its admittance matrix $\underline{\mathbf{Y}}_\mathbf{g}$, and an active part, modeled with a Norton equivalent. Compared to dealing with a Thevenin equivalent, the Norton equivalent simplifies the formulation since it does not create an additional bus. The VSCs are treated as current sources that inject currents of the form of $\underline{I}_k \forall k \in [1, ..., n]$. Additional impedances denoted by $\underline{Z}_{vk}$ connect the point of common coupling to the grid. Such point of common coupling is precisely where the voltages ought to be improved.

The relationship between currents and voltages can be established with an analysis in the natural reference frame or by employing symmetrical components as in [22]. Although both approaches are equally valid, working in the natural reference frame allows studying the system with greater flexibility, as only the particular elements of the admittance matrices that depend on the fault admittance experience changes. No other modifications in the topology have to be considered. Consequently, voltages and currents are related by

$$\begin{pmatrix} \underline{\mathbf{I}}_\mathbf{1} \\ \underline{\mathbf{I}}_\mathbf{2} \\ \vdots \\ \underline{\mathbf{I}}_\mathbf{n} \\ \underline{\mathbf{I}}_\mathbf{t} \end{pmatrix} = \begin{pmatrix} \underline{\mathbf{Y}}_\mathbf{v1} & \mathbf{0} & \dots & \mathbf{0} & -\underline{\mathbf{Y}'}_\mathbf{v1} \\ \mathbf{0} & \underline{\mathbf{Y}}_\mathbf{v2} & \dots & \mathbf{0} & -\underline{\mathbf{Y}'}_\mathbf{v2} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \mathbf{0} & \mathbf{0} & \dots & \underline{\mathbf{Y}}_\mathbf{vn} & -\underline{\mathbf{Y}'}_\mathbf{vn} \\ -\underline{\mathbf{Y}'}^\mathbf{T}_\mathbf{v1} & -\underline{\mathbf{Y}'}^\mathbf{T}_\mathbf{v2} & \dots & -\underline{\mathbf{Y}'}^\mathbf{T}_\mathbf{vn} & \underline{\mathbf{Y}}_\mathbf{g} \end{pmatrix} \begin{pmatrix} \underline{\mathbf{V}}_\mathbf{p1} \\ \underline{\mathbf{V}}_\mathbf{p2} \\ \vdots \\ \underline{\mathbf{V}}_\mathbf{pn} \\ \underline{\mathbf{V}}_\mathbf{g} \end{pmatrix}. \tag{1}$$

For a given converter k, its injected currents and its associated voltages at the point of common coupling are further developed as

$$\begin{cases} \underline{\mathbf{I}}_\mathbf{k} = \left[\underline{I}_k^{(a)}, \underline{I}_k^{(b)}, \underline{I}_k^{(c)}\right]^T \\ \underline{\mathbf{V}}_\mathbf{pk} = [\underline{V}_{pk}^{(a)}, \underline{V}_{pk}^{(b)}, \underline{V}_{pk}^{(c)}]^T \end{cases} \tag{2}$$

i.e., they contain the a, b and c phase values. Voltages and currents are related via admittance matrices of the form $\underline{\mathbf{Y}}_\mathbf{vk}$, which in normal operating conditions follow

$$\underline{\mathbf{Y}}_\mathbf{vk} = \begin{pmatrix} \frac{1}{\underline{Z}_{vk}} & 0 & 0 \\ 0 & \frac{1}{\underline{Z}_{vk}} & 0 \\ 0 & 0 & \frac{1}{\underline{Z}_{vk}} \end{pmatrix}. \tag{3}$$

In case a fault occurs at the buses interconnected by $\underline{Z}_{vk}$, elements $1/\underline{Z}_f$ are added by observation, where $\underline{Z}_f$ denotes the fault impedance.

On the contrary, the admittance matrix $\underline{\mathbf{Y}}_\mathbf{g}$ is a $3n_g \times 3n_g$ matrix also built by observation. The object $\underline{\mathbf{I}}_\mathbf{t}$ is a vector of dimensions $3 \times n_g$ which accounts for the injected currents into the grid denoted by $\underline{\mathbf{Y}}_\mathbf{g}$. All its elements are null except for three entries that consider the injected currents from the Norton equivalent of the grid. Matrices of the form $\underline{\mathbf{Y}'}_\mathbf{vk}$ are $3 \times 3n_g$ objects constituted by elements $1/\underline{Z}_{vk}$. In a realistic scenario, the grid $\underline{\mathbf{Y}}_\mathbf{g}$ may be partially constitued by active and reactive power loads, i.e., PQ buses. They can be either ignored if the current they consume is assessed to be comparatively smaller than the fault current, or they can be modeled as constant admittances. No PQ loads have been considered in the case studies shown in this paper.

The final goal of the modeling is the obtention of voltages. They are computed from (1) by operating the product between the inverse of the full admittance matrix and the currents' vector. In order to have a clearer comprehension of the voltages, they are eventually converted into symmetrical components by means of Fortescue's transformation [23]:

$$\begin{pmatrix} \underline{V}^0_{pk} \\ \underline{V}^+_{pk} \\ \underline{V}^-_{pk} \end{pmatrix} = \frac{1}{3} \begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix} \begin{pmatrix} \underline{V}^a_{pk} \\ \underline{V}^b_{pk} \\ \underline{V}^c_{pk} \end{pmatrix} , \tag{4}$$

where $a = e^{j\frac{2\pi}{3}}$.

B. Optimization problem

Positive sequence voltages have to be maximized while negative sequence voltages have to be minimized. The zero sequence component of the voltages is a magnitude likely to become non-null under asymmetrical faults. Nevertheless, as VSC are unable to inject zero sequence currents, it will remain an uncontrolled variable in the sense that no efforts will be made towards reducing it. Current saturation restrictions imposed by the VSC characteristics have to be respected. This applies to each phase of each converter. Therefore, the generic optimization problem is

$$\begin{aligned} \min_{\underline{I}} \quad & \sum_{k=1}^{n} \Big[\lambda_k^+ |(1 - |\underline{V}^+_{pk}(\underline{I})|)| + \lambda_k^- |(0 - |\underline{V}^-_{pk}(\underline{I})|)|\Big] , \\ \text{s.t.} \quad & \max(\underline{I}^a_k, \underline{I}^b_k, \underline{I}^c_k) \leq I_{\text{max,k}} \ \forall k \in [1, ..., n] , \\ & \underline{I}^a_k + \underline{I}^b_k + \underline{I}^c_k = 0 \ \forall k \in [1, ..., n] , \end{aligned} \tag{5}$$

where the positive and negative sequence components of voltages $\underline{V}_{pk}$ are symbolically expressed as functions of the currents, and $I_{\text{max,k}}$ is the maximum allowed current by the k converter. It has been assumed that voltages at each phase of the converter do not surpass the limitations, which seems a fair assumption considering that voltages decreases substantially during faults. Ignoring voltage limitations tends to be a commonality in the literature as well.

The results gathered in this paper are computed with Python 3.9.1 and the aid of the Mystic package, a highly-constrained non-convex optimization framework [24], [25]. A differential global optimization solver has been employed with a relative precision up to $1e-6$.

C. Grid code rules

In order to improve voltages during faults, grid code control rules typically impose injections of currents proportional to the voltage drop [8], [26]. When defined as piecewise functions, for the positive sequence

$$\begin{cases} |\underline{I}^+_k| = 0 & |\underline{V}^+_{pk}| \geq 0.9 \\ |\underline{I}^+_k| = k_p(0.9 - |\underline{V}^+_{pk}|) & 0.5 \leq |\underline{V}^+_{pk}| < 0.9 \\ |\underline{I}^+_k| = 1 & |\underline{V}^+_{pk}| < 0.5 \end{cases} \tag{6}$$

whereas for the negative sequence

$$\begin{cases} |\underline{I}^-_k| = 0 & |\underline{V}^-_{pk}| \leq 0.1 \\ |\underline{I}^-_k| = k_n(|\underline{V}^-_{pk}| - 0.1) & 0.1 \leq |\underline{V}^-_{pk}| < 0.5 \\ |\underline{I}^-_k| = 1 & |\underline{V}^-_{pk}| > 0.5 \end{cases} \tag{7}$$

Both constants k_p and k_n are set at 1.25. This value was found to be the theoretical maximum so that current limitations are not reached in the worst case scenario where $|\underline{V}^+_{pk}| = 0.5$ and $|\underline{V}^-_{pk}| = 0.5$.

The application of the grid code rules implies that maximum phase currents are hardly ever equal to the maximum allowed by the VSC, even when strong faults occur. Thus, an adaptative control can be formulated so that currents tend to the maximum permitted value while the droop characteristic is preserved. This strategy is denoted by ADA, as in essence it consists of an adaptative mechanism. In order to fairly compare between methodologies, k_p and k_n are always equal. A central goal of this paper is concerned with determining beforehand the value of $k_p = k_n$, i.e., independently of fault voltages.

D. Summary of support techniques

The paper evaluates and compares three support strategies, which are:

- OPT: corresponds to the solution of the optimization problem in (5), particularized for each system. It provides, by definition, the best solution.
- GC: is the application of the grid code rules shown in (6) and (7), with $k_p = k_n = 1.25$. It should generate the less convenient solution out of the three analyzed strategies.
- ADA: mimics the grid code rules from (6) and (7) with an adapted value of the constants $k_p = k_n$ so that the VSC operates close to the current limitations.

III. Single converter case study

The analysis is first performed considering a one-converter case study as the one depicted in Figure 3. A fault is caused at the point of connection of the grid. The impedances that model the fault are set accordingly to the type of fault, i.e., balanced or unbalanced (line to ground, line to line or double line to ground). The goal is to improve the voltage $\underline{V}_{p1}$ by injecting the optimal $\underline{I}^a_1$, $\underline{I}^b_1$ and $\underline{I}^c_1$ currents.

Three parametric studies are performed. One considers variations in the fault impedance. This case is explicitly described in order to exemplify the formulation. Another study analyzes a varying R_1/X_1 ratio, i.e., the proportion

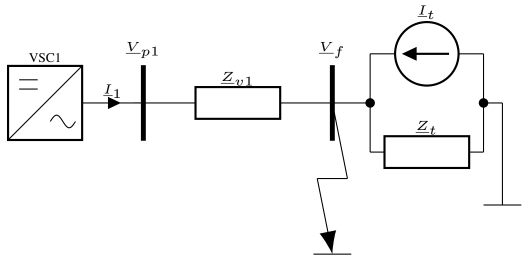

Fig. 3: Single-phase representation of the single converter system under study

between the resistive and the inductive parts that compose the impedance $\underline{Z}_{v1}$ is modified while the absolute value of the impedance is kept constant. The third case presents the effect of increasing the distance of a hypothetical submarine cable.

A. *Fault impedance variation analysis*

For a single converter system as the one depicted in Figure 3, the fault impedance connected to the bus at voltage $\underline{V}_f$ is responsible for identify the fault. Explicitly, voltages and currents are related by

$$\begin{pmatrix} \underline{I}_1^a \\ \underline{I}_1^b \\ \underline{I}_1^c \\ \underline{I}_t^a \\ \underline{I}_t^b \\ \underline{I}_t^c \end{pmatrix} = (\underline{\mathbf{Y}}_\mathbf{v} + \underline{\mathbf{Y}}_\mathbf{f}) \begin{pmatrix} \underline{V}_{p1}^a \\ \underline{V}_{p1}^b \\ \underline{V}_{p1}^c \\ \underline{V}_f^a \\ \underline{V}_f^b \\ \underline{V}_f^c \end{pmatrix} , \tag{8}$$

where the admittance matrix has been split into two parts: $\underline{\mathbf{Y}}_\mathbf{v}$ represents the non-faulted admittance matrix of the system, whereas $\underline{\mathbf{Y}}_\mathbf{f}$ is constitued by the admittances that intervene in the fault. This way, the admittance matrices are defined as

$$\underline{\mathbf{Y}}_\mathbf{v} = \begin{pmatrix} \underline{Y}_{v1} & 0 & 0 & -\underline{Y}_{v1} & 0 & 0 \\ 0 & \underline{Y}_{v1} & 0 & 0 & -\underline{Y}_{v1} & 0 \\ 0 & 0 & \underline{Y}_{v1} & 0 & 0 & -\underline{Y}_{v1} \\ -\underline{Y}_{v1} & 0 & 0 & \underline{Y}_{v1}+\underline{Y}_t & 0 & 0 \\ 0 & -\underline{Y}_{v1} & 0 & 0 & \underline{Y}_{v1}+\underline{Y}_t & 0 \\ 0 & 0 & -\underline{Y}_{v1} & 0 & 0 & \underline{Y}_{v1}+\underline{Y}_t \end{pmatrix} \tag{9}$$

where $\underline{Y}_{v1} = 1/\underline{Z}_{v1}$ and $\underline{Y}_t = 1/\underline{Z}_t$.

On the other hand, the fault admittance $\underline{\mathbf{Y}}_\mathbf{f}$ is fully dependent on the fault and therefore, it is built by observation. The optimization problem for the one case converter reads

$$\begin{aligned} \min_{\underline{I}_1^a, \underline{I}_1^b, \underline{I}_1^c} \quad & \lambda_1^+ |(1 - |\underline{V}_{p1}^+(\underline{I}_1^a, \underline{I}_1^b, \underline{I}_1^c)|)| \\ & + \lambda_1^- |(0 - |\underline{V}_{p1}^-(\underline{I}_1^a, \underline{I}_1^b, \underline{I}_1^c)|)| \ , \\ \text{s.t.} \quad & \max(\underline{I}_1^a, \underline{I}_1^b, \underline{I}_1^c) \leq I_{\max,1} \ , \\ & \underline{I}_1^a + \underline{I}_1^b + \underline{I}_1^c = 0 \ , \end{aligned} \tag{10}$$

The procedure to solve the optimization problem is first responsible for initializing the admittances matrices $\underline{\mathbf{Y}}_\mathbf{v}$ as in (9), and then, constructing $\underline{\mathbf{Y}}_\mathbf{f}$. Next, currents are initialized to a random array of values, for instance. The Mystic package is subsequently called to solve the optimization problem stated in (10) up to a given relative precision δ, being $\delta = 1e-6$ for example. Positive and negative sequence voltages are evaluated to determine the optimality of the solution by means of (4).

TABLE I: System parameters for the one-converter case

Parameter	Value
$\underline{V}_t$	1.00
$I_{\max}$	1.00
$\underline{Z}_{v1}$	$0.01 + j0.05$
$\underline{Z}_t$	$0.01 + j0.1$
$[\lambda_1^+, \lambda_1^-]$	$[1, 1]$

In case of sweeping a range of n scenarios, this process is repeated n times. Currents are eventually also transformed to positive and negative sequence values, since the final goal is to evaluate their values in this frame of reference. Unless noted otherwise, the corresponding baseline parameters of the system in Figure 3 are indicated in Table I.

Solving the problem with the aforementioned steps for a balanced fault yields the results shown in Figure 7, where impedance $\underline{Z}_x$ denotes the fault impedance connected to each phase. The OPT case stands for the solution to (10); GC represents the solution obtained with the grid code expressions (6) and (7). The results suggest that the optimal case is the preferred one, as its associated objective function is always the smallest, as expected. However, the GC solution does not substantially differ from it. In all cases the VSC operates at saturation conditions, yet the distribution of currents varies.

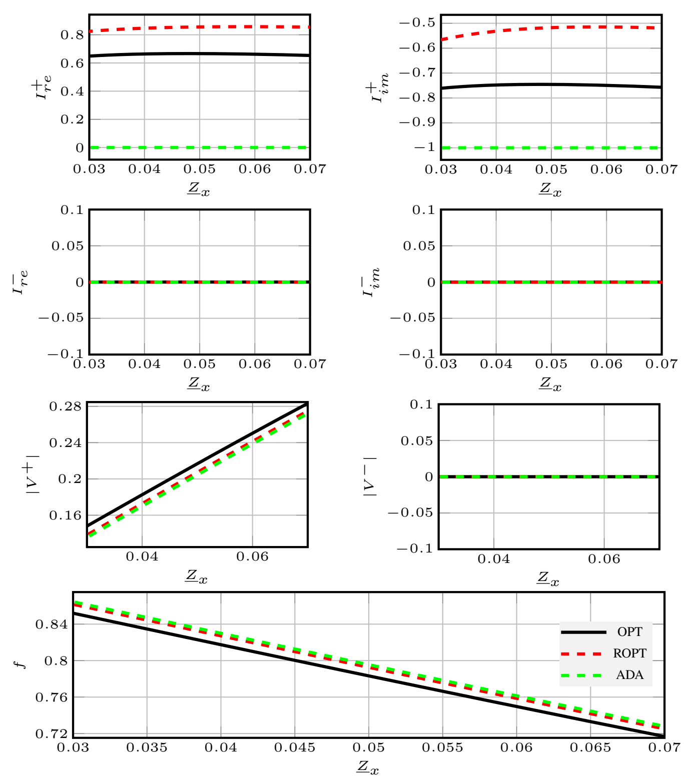

Fig. 4: Influence of the currents on the objective function for the balanced fault with a varying fault admittance, one converter case

Negative sequence currents are null, just like it could be foreseen for any balanced fault. The GC solution only injects imaginary positive sequence as real currents are not allowed by definition. The OPT solution achieves the optimal distribution

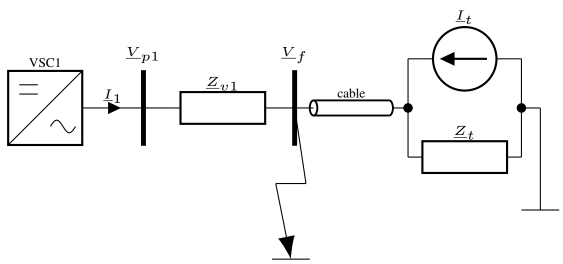

Fig. 5: Single-phase representation of the single converter connected to a system with a cable

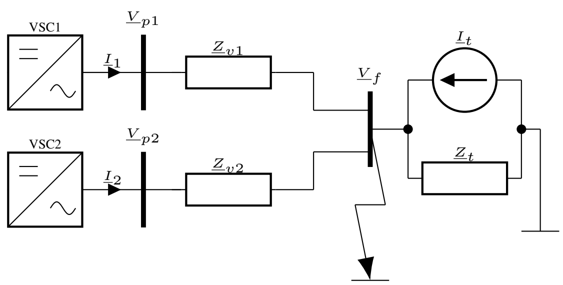

Fig. 6: Single-phase representation of the two-converter system under study

of currents. The current capabilities of the converter are roughly equally attributed to the real and imaginary positive sequence currents. Despite these differences, the GC solution is not significantly worse than the optimal.

B. R/X variation analysis

C. Cable length variation analysis

The methodology to optimize voltages under a given fault is shortly described with the intention of presenting the main steps involved.

IV. Two converter case study

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A. Fault impedance variation analysis

B. R/X variation analysis

TABLE II: System parameters for the two converter case

Parameter	Value
$\underline{V}_t$	1.00
$I_{\max}$	1.00
$\underline{Z}_{v1}$	$0.01 + j0.05$
$\underline{Z}_{v2}$	$0.01 + j0.06$
$\underline{Z}_t$	$0.01 + j0.1$
$[\lambda_1^+, \lambda_1^-, \lambda_2^+, \lambda_2^-]$	$[1, 1, 1, 1]$

V. ////////////PLOTS////////////

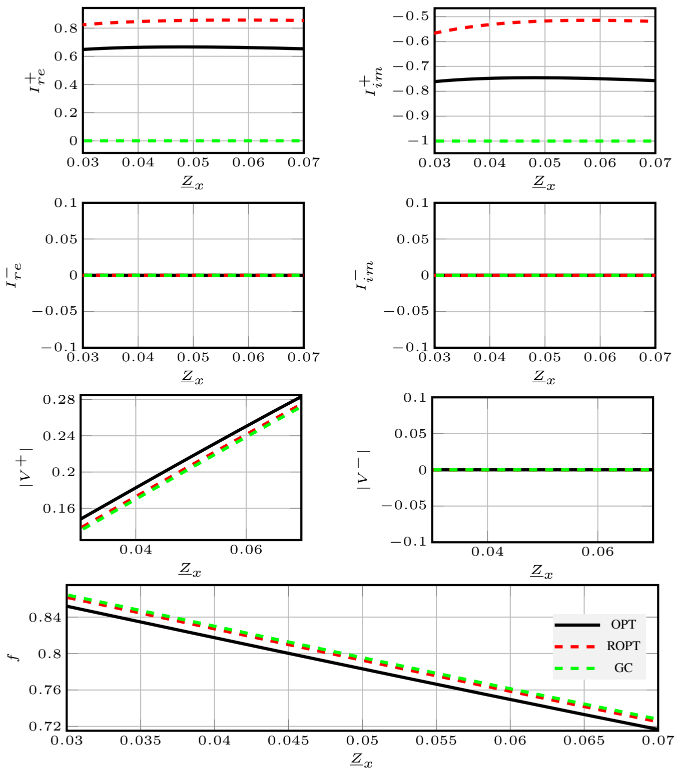

Fig. 7: Influence of the currents on the objective function for the balanced fault with a varying fault admittance, one converter case

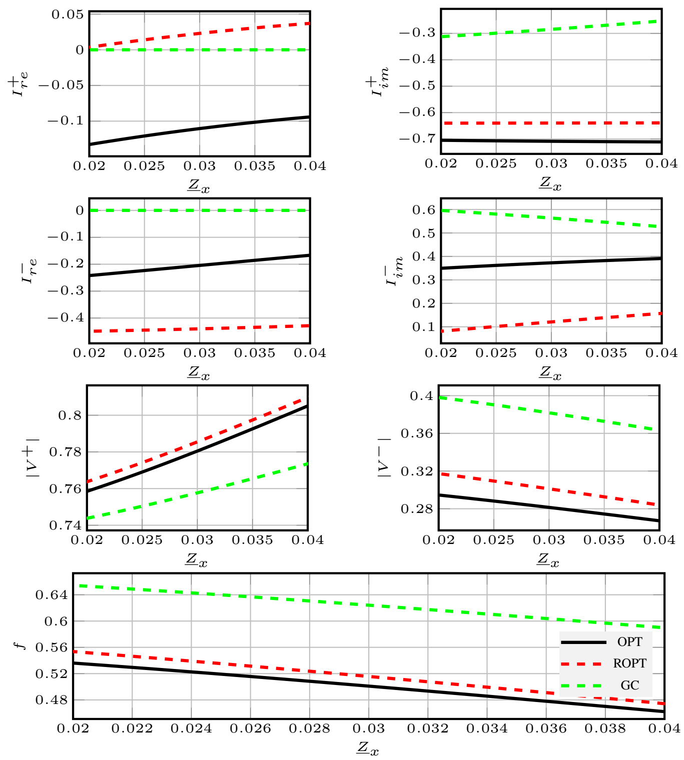

Fig. 8: Influence of the currents on the objective function for the line to ground with a varying fault admittance, one converter case

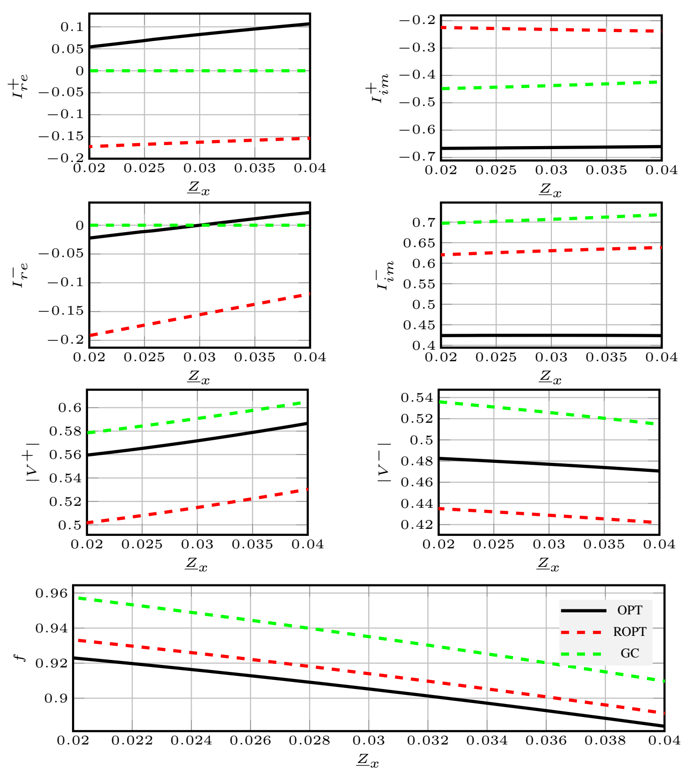

Fig. 9: Influence of the currents on the objective function for the line to line with a varying fault admittance, one converter case

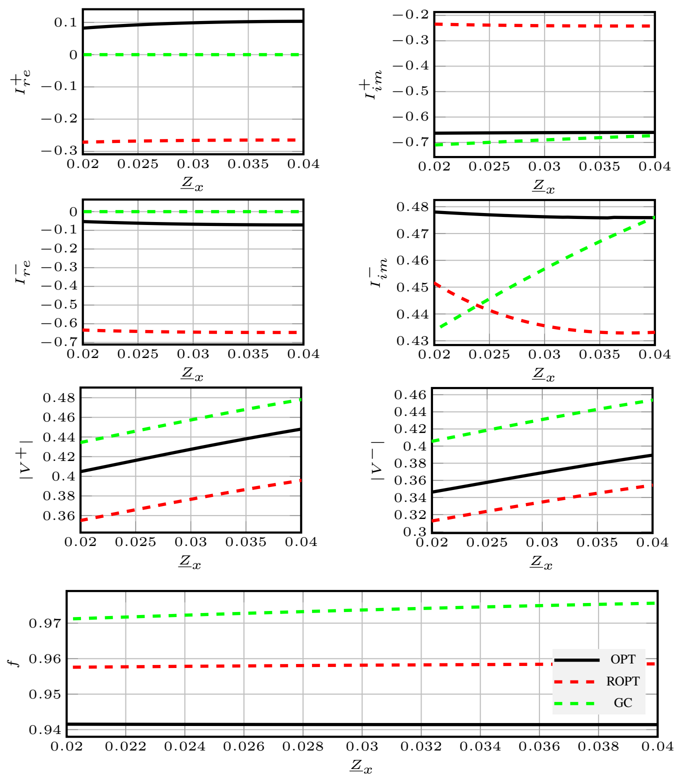

Fig. 10: Influence of the currents on the objective function for the double line to ground with a varying fault admittance, one converter case

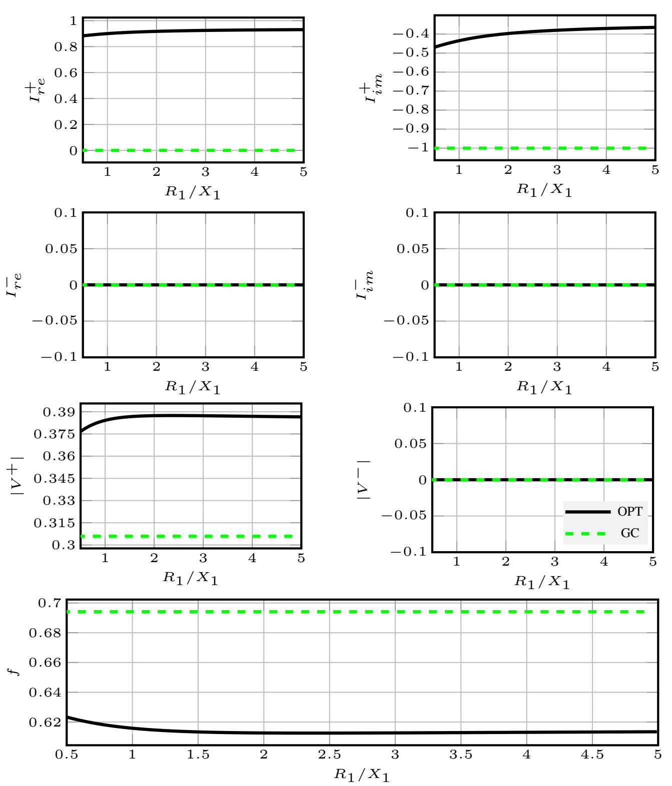

Fig. 11: Influence of the currents on the objective function for the balanced fault with a varying R_1/X_1 ratio and $\underline{Z}_x = 0.1$

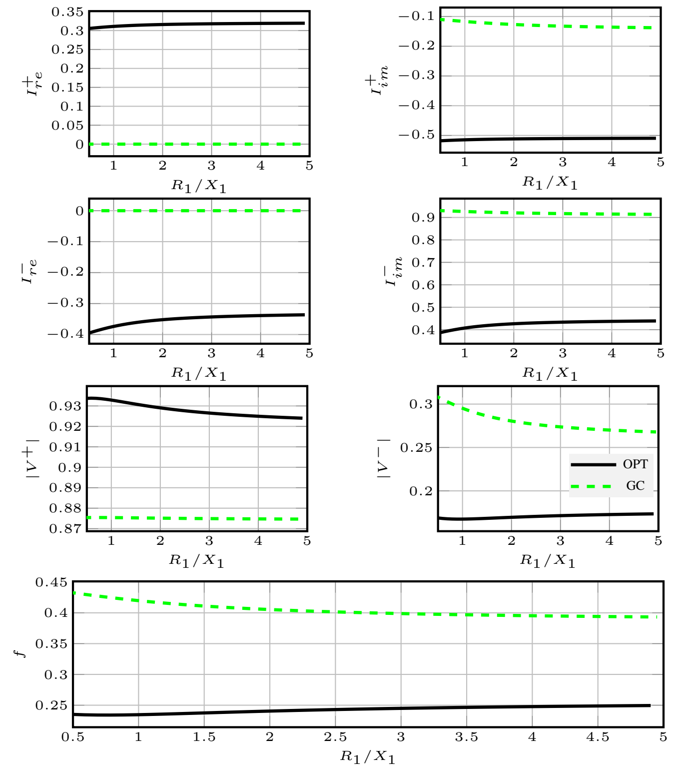

Fig. 12: Influence of the currents on the objective function for the line to ground fault with a varying R_1/X_1 ratio and $\underline{Z}_{ag} = 0.1$

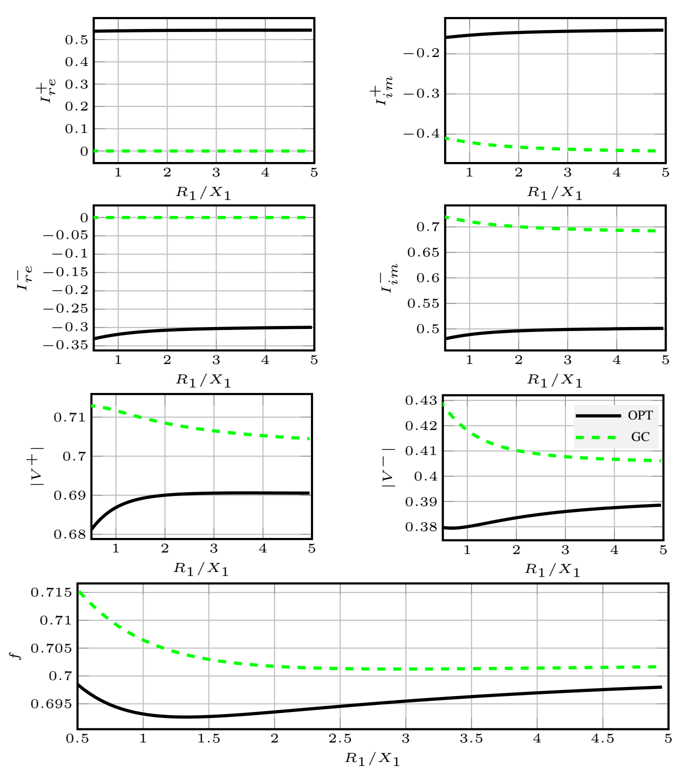

Fig. 13: Influence of the currents on the objective function for the line to line fault with a varying R_1/X_1 ratio and $\underline{Z}_{ab} = 0.1$

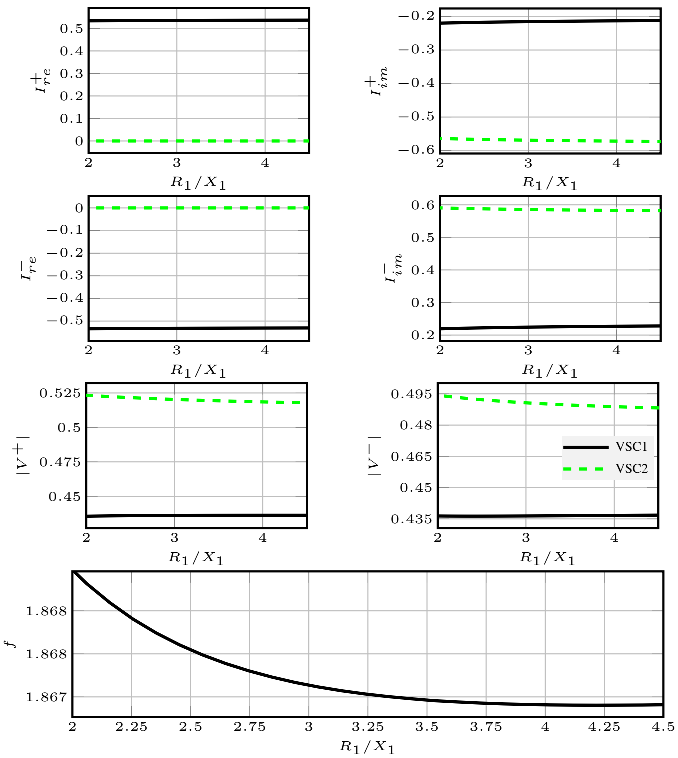

Fig. 14: Influence of the currents on the objective function for the double line to ground fault with a varying R_1/X_1 ratio and $\underline{Z}_{ag} = 0.1$

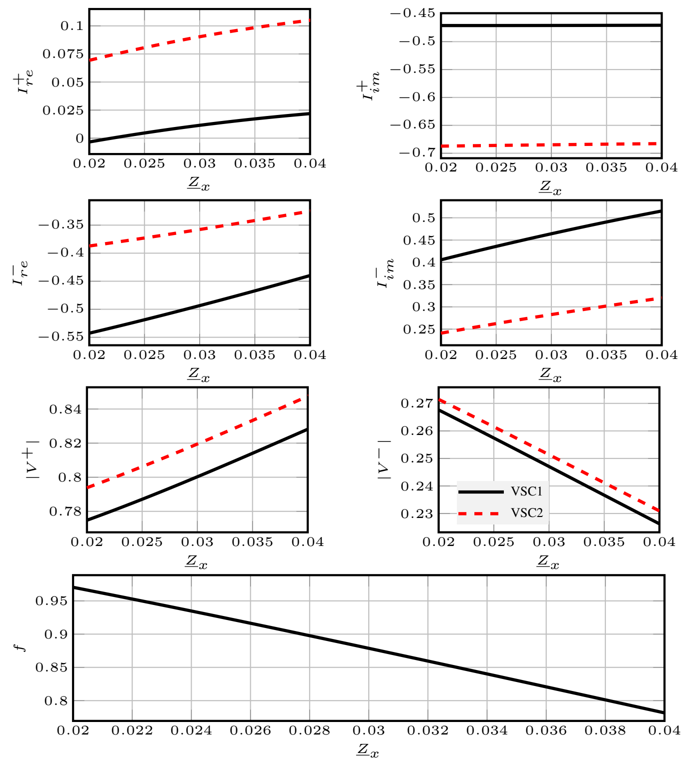

Fig. 16: Influence of the currents on the objective function for the line to ground with a varying fault admittance

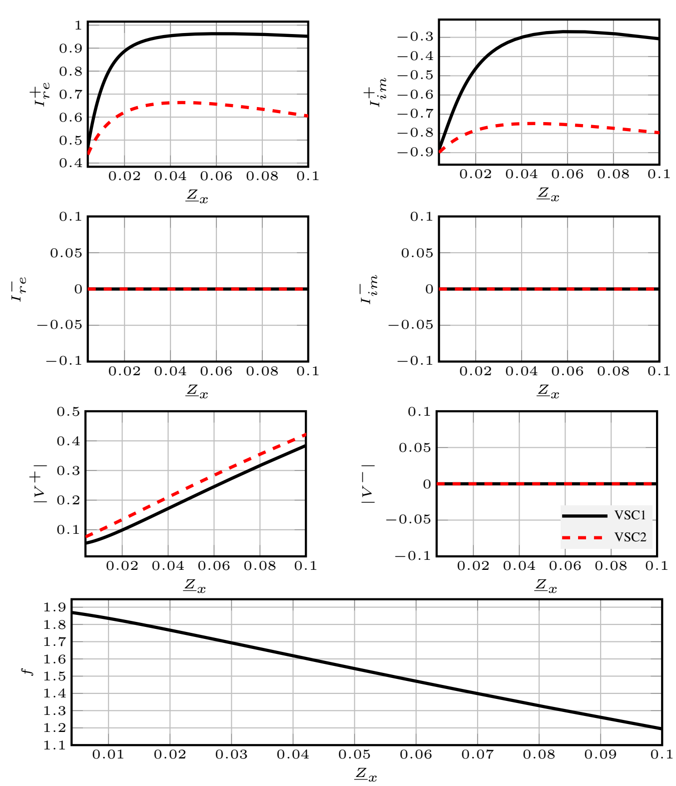

Fig. 15: Influence of the currents on the objective function for the balanced fault with a varying fault admittance

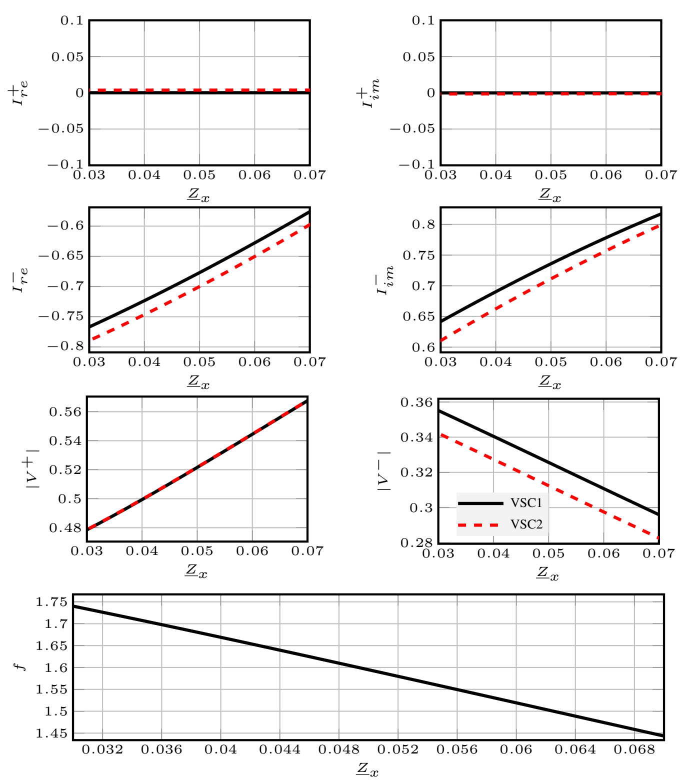

Fig. 17: Influence of the currents on the objective function for the line to line with a varying fault admittance

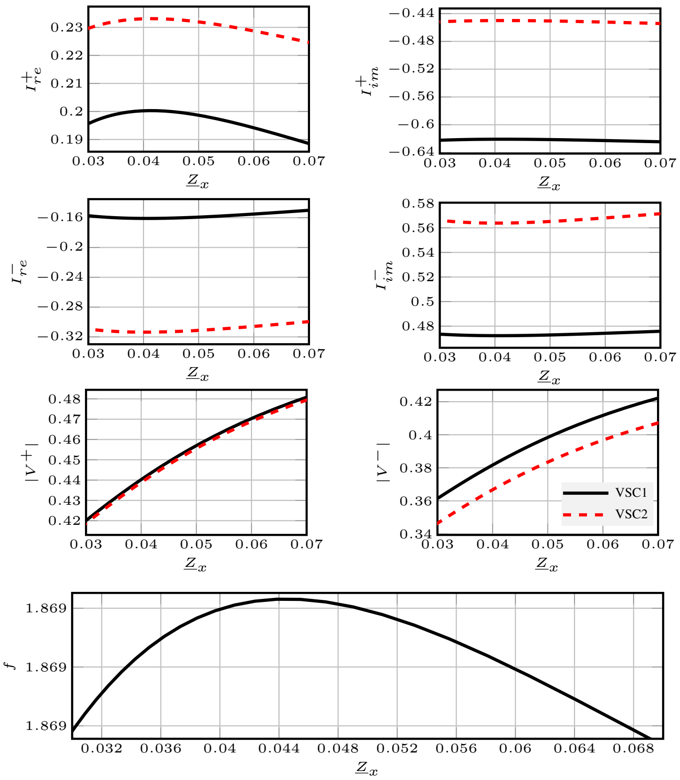

Fig. 18: Influence of the currents on the objective function for the double line to ground with a varying fault admittance

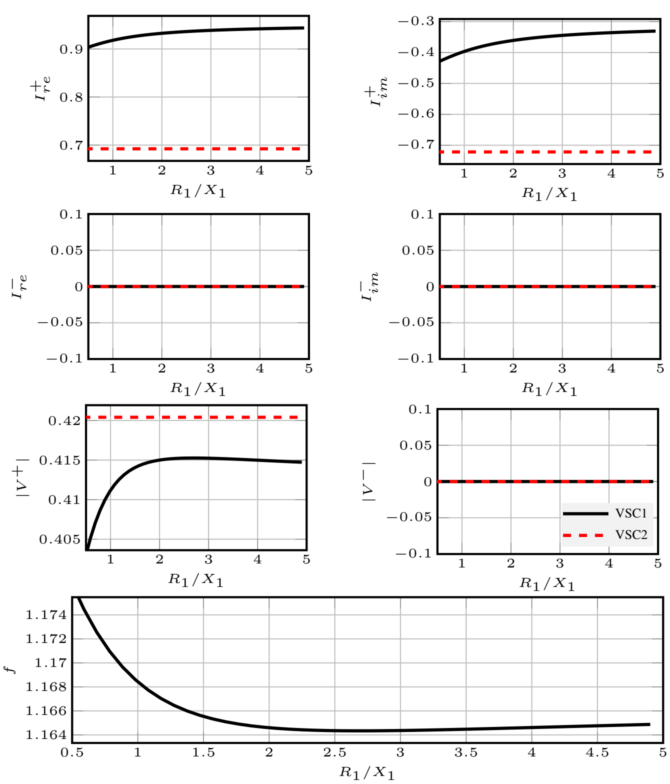

Fig. 19: Influence of the currents on the objective function for the balanced fault with a varying R_1/X_1 ratio and $\underline{Z}_x = 0.1$

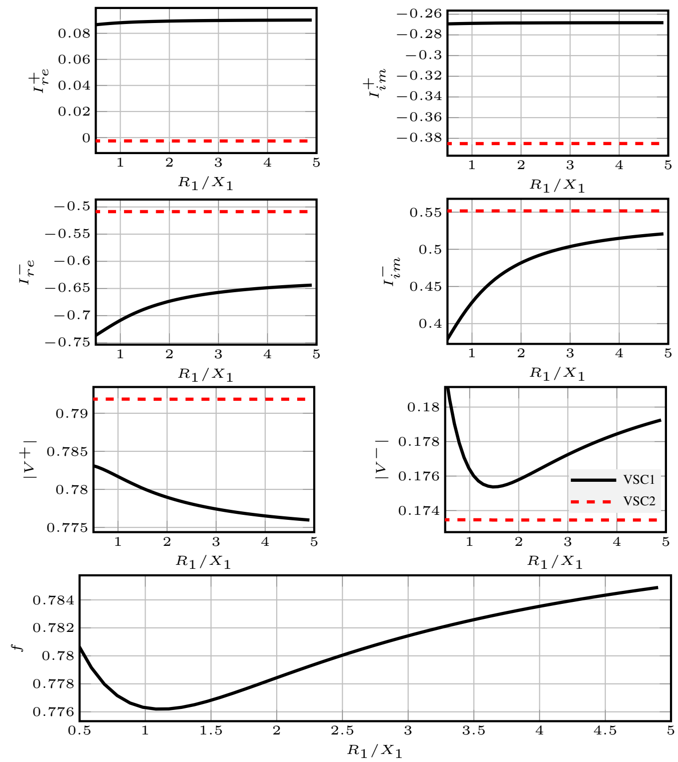

Fig. 20: Influence of the currents on the objective function for the line to ground fault with a varying R_1/X_1 ratio and $\underline{Z}_{ag} = 0.04$

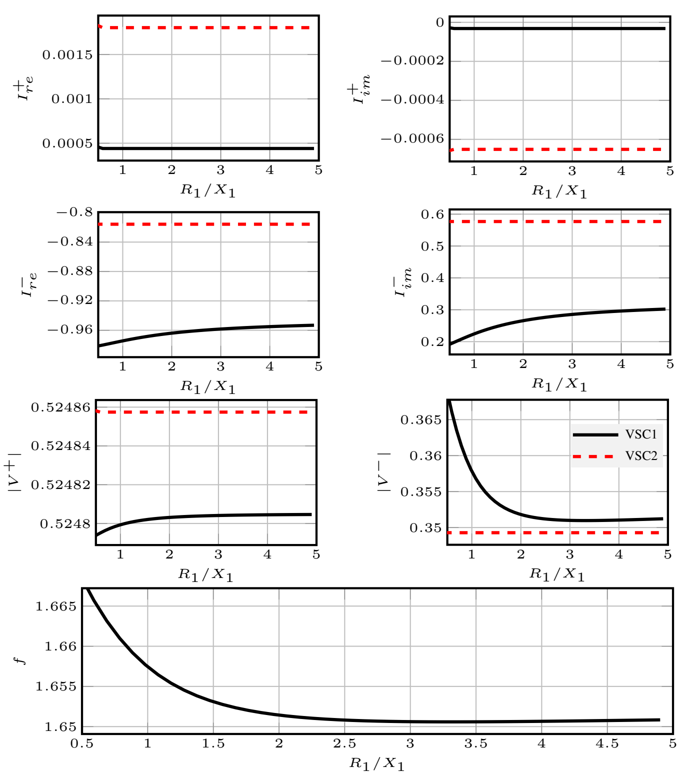

Fig. 21: Influence of the currents on the objective function for the line to line fault with a varying R_1/X_1 ratio and $\underline{Z}_{ab} = 0.04$

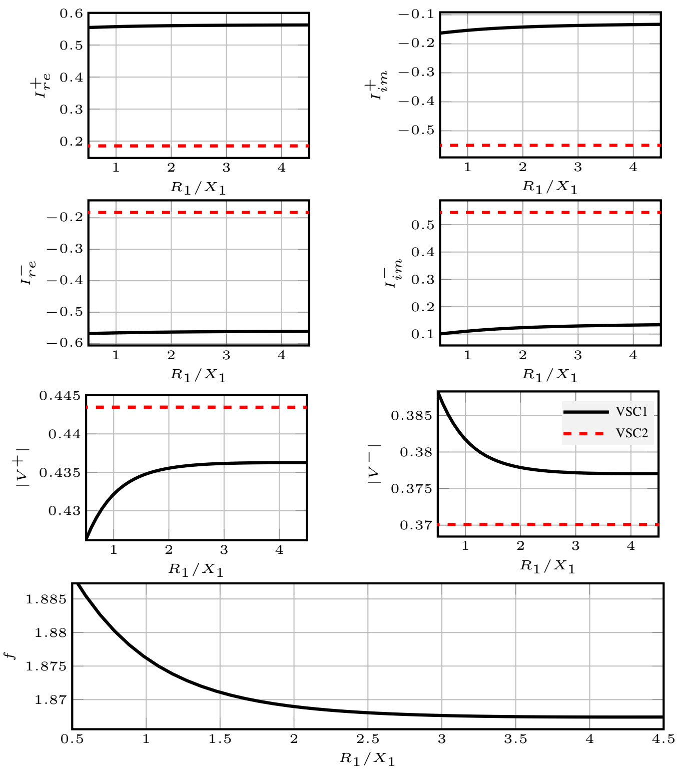

Fig. 22: Influence of the currents on the objective function for the double line to ground fault with a varying R_1/X_1 ratio and $\underline{Z}_{ag} = 0.04$

VI. Conclusion

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Acknowledgment

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